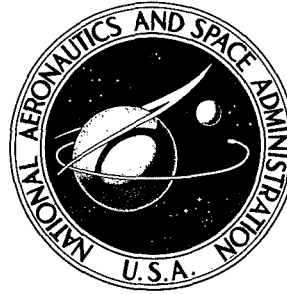


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**DESIGN AND PERFORMANCE
OF A HIGH-FREQUENCY
WATTAGE-TO-VOLTAGE CONVERTER**

by James E. Vrancik

*Lewis Research Center
Cleveland, Ohio*

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16. Abstract <p>A solid-state wattage-to-dc-voltage converter, using a state-of-the-art electronic analog multiplier, was designed and tested. The unit provides a dc output voltage proportional to the instantaneous product of two input signals. If the input signals represent the current and voltage in the circuit being tested, the output is proportional to the power of the circuit. The converter was found to have an accuracy of 0.2 percent of full scale over a frequency range from dc to 15 kHz for unity power factor. The accuracy decreased to 0.7 percent of full scale for power factors from 0 to 1 at 1 kHz. The slewing rate was $2V/\mu\text{sec}$.</p>			
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DESIGN AND PERFORMANCE OF A HIGH-FREQUENCY WATTAGE-TO-VOLTAGE CONVERTER

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SUMMARY

A solid-state wattage-to-voltage converter was designed and tested. The device generates an output voltage proportional to the product of two input voltages. When the two input voltages represent the voltage and current in the circuit being tested, the output is proportional to instantaneous power. The average output voltage was a measure of average power.

The product of the two input signals was obtained by using a state-of-the-art high-speed electronic analog multiplier. The converter was tested and found to be accurate to within 0.2 percent of full scale over a frequency range from dc to 15 kilohertz for unity power factor. The accuracy decreased to 0.7 percent of full scale for power factors from 0 to 1 at 1 kilohertz. The slewing rate was found to be 2 volts per microsecond.

INTRODUCTION

Alternating-current power is presently measured by devices such as the electrodynamicometer and induction-type wattmeters, the thermal converter, and the calorimeter. These devices serve their intended purposes, but they have basic limitations that restrict their scope of usefulness. These limitations are a limited frequency range, a long step-response time, a large error with low-power-factor loads or high-distortion waves, and the consumption of a substantial amount of power from the circuit being measured.

This report describes a new device for measuring electric power over a wide frequency range. It uses a converter in which two electrical input signals produce an output voltage linearly proportional to the instantaneous product of the two input signals. If the two input signals are proportional to the current and the voltage in the circuit

being measured, the output voltage is proportional to the instantaneous power. It is shown that this method of measuring high-frequency power provides the capability of making measurements over a wide frequency range with high accuracy, fast step response, and high input and low output impedance.

The heart of the converter is an electronic analog multiplier. Multipliers have been used in analog computers for years but, until recently, they have been limited to applications below several hundred hertz. References 1 to 5 describe salient characteristics and applications of available analog multipliers. Currently, the quarter-square type of multiplier has the most desirable characteristics of high-frequency response and high accuracy, so it was selected for this study. A test device was built using this multiplier and other available state-of-the-art components. The construction and test results are described herein.

Another device for measuring power at high frequency and presently under development exploits the Hall effect. This device uses the same concept as the wattage-to-voltage converter described herein, but a Hall-effect multiplier replaces the quarter-square multiplier.

HIGH-FREQUENCY WATTAGE CONVERTER CONCEPT AND DESIGN

Electric power is defined as the product of voltage times current, and the average power is the average product. If a device were available that could convert two input signals into the product of the two signals, that device could be used to measure power. The average output would be proportional to the average power and would be independent of wave shape and power factor. But possibly even more important, the instantaneous product would be proportional to the instantaneous power. And if the conversion rate were very fast (less than 1 μ sec), high-frequency peaks of power could be measured, and high-frequency sine-wave power could also be measured by filtering the output and measuring the dc output voltage. Prior to this time, high-frequency power pulses could not be measured accurately with conventional wattmeters.

The requirements of a device to accurately measure electric power at high frequency are as follows:

- (1) There must be two input channels which do not draw significant power from the circuit being tested and which do not distort the input signals.

- (2) Means must exist of accurately providing an instantaneous product of the two input voltage signals to produce a single output voltage.

- (3) There must be a way of measuring the product output voltage without distortion. (The output circuit must have a low output impedance.)

A design concept, which used these requirements, employing an analog multiplier to perform the instantaneous multiplication of two impulses is illustrated in block diagram

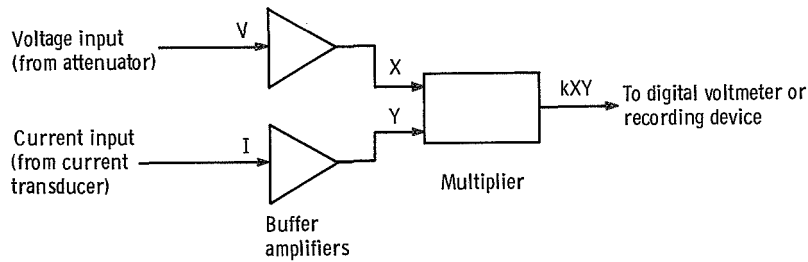


Figure 1. - Block diagram of wattage-to-voltage converter.

form in figure 1. This concept is used in the wattage-to-voltage converter described herein. Since there are a number of types of analog multipliers available, the decision to use the quarter-square-type multiplier was based on the fact that it gave the best combination of high accuracy and high-frequency response (ref. 5). Reference 4 gives a detailed explanation in the theory of operation of a quarter-square multiplier.

Unity-gain buffer amplifiers were added to the inputs to achieve the necessary high input impedance because the multiplier chosen had a low input impedance (10 k Ω). Using these amplifiers reduces loading and distortion.

The current input signal is supplied by a commercially available high-frequency current transformer with a built-in shunt resistor to produce an output voltage signal proportional to the current input. Standard high-frequency current transformers having

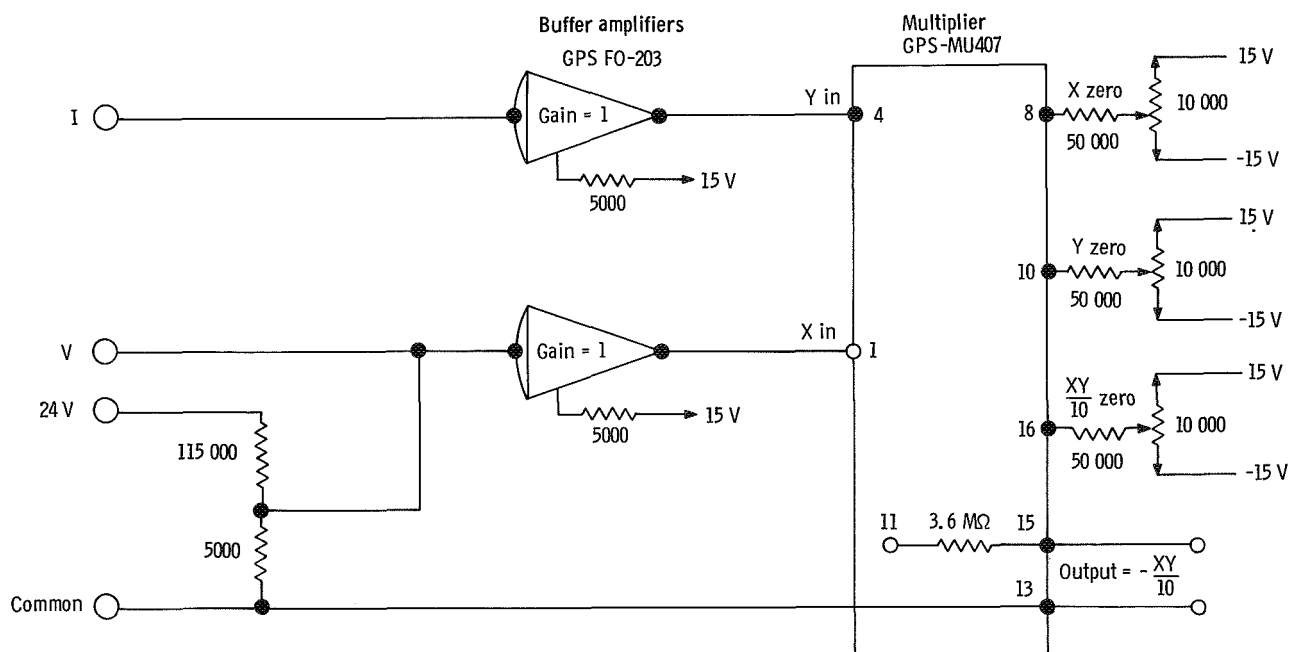


Figure 2. - Schematic diagram of wattage-to-voltage converter. (Power supply connections not shown.)



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Figure 3. - Wattage-to-voltage converter.

rated inputs ranging from 1 to 500 amperes and producing a 5-volt full-scale output are available and can be used with this converter.

The ac voltage input to the buffer (and also to the multiplier) is limited to ± 10 volts peak, so an attenuator was necessary to reduce larger signals to the proper level.

The schematic of the actual unit constructed is shown in figure 2. The trim pots shown were used to accurately set the supply voltage and balance out the various offsets. The high-frequency wattage-to-voltage converter is shown in figure 3.

TEST PROCEDURE

The wattage converter was tested to determine the ability of the multiplier to generate the product of the two input signals which were representative of the signals the wattage converter would experience in practical applications. The tests did not include the effect of the current transformers or the input voltage attenuator on the dc output. The attenuator was connected, however, which reduced the input resistance of the low voltage V input to 5000 ohms. The specific tests performed include:

- (1) DC input voltage test
- (2) AC input voltage test at constant frequency and unity power factor
- (3) Frequency response test at constant input voltage and unity power factor
- (4) Phase angle test at constant voltage and frequency

(5) Drift test

(6) Rise time test

The details of these tests are now described.

DC Voltage Test

The purpose of this test was to determine the accuracy of the converter when finding the product of two dc input voltages. The apparatus for this test is shown in figure 4. All digital voltmeters (DVM's) were of the dc integrating type. The DVM on the output for all tests was of the dc integrating type and had an integration time of 1 second. The dc voltages for both the V and I inputs ranged from 0 to 10 volts.

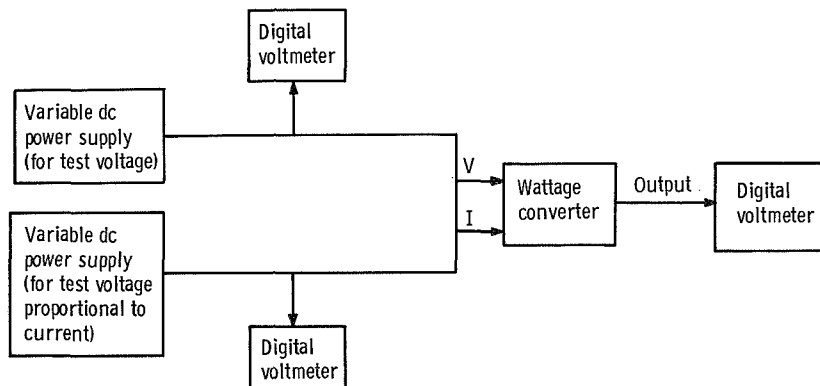


Figure 4. - Test circuit for dc input test.

AC Voltage Test

This test was made to determine the accuracy of the converter when finding the product of two in-phase ac voltages. The apparatus for the ac voltage test is shown in figure 5. The ac test was conducted over a range of 0 to 5 volts rms to both the V and I inputs at 1 kilohertz and unity power factor (phase angle was zero). The DVM's on the input signal terminals were average responding rms calibrated. Input voltage was provided by means of a variable frequency, variable voltage source.

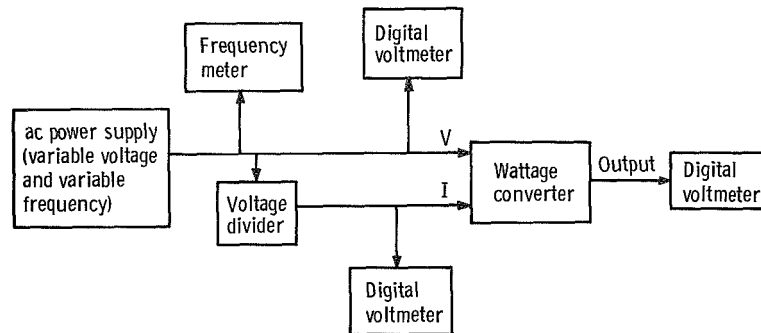


Figure 5. - Test circuit for ac input and frequency test.

Frequency Response Test

The purpose of this test was to determine the frequency response of the converter. The apparatus for the frequency test was the same as that used in the previous test (see fig. 5). The voltage input was set at two test levels. In the first test both inputs were identical and set at 5 volts rms. In the second test one input was set at 5 volts rms and the other input was set at 1 volt rms. The test frequency range was from 100 hertz to 100 kilohertz.

Phase Angle Test

This test was made to determine the effect of phase angle between the two input signals on the accuracy of the converter output. The apparatus for the phase angle test is shown in figure 6.

The phase angle test was conducted over a phase angle range of 0° to 130° . The ac

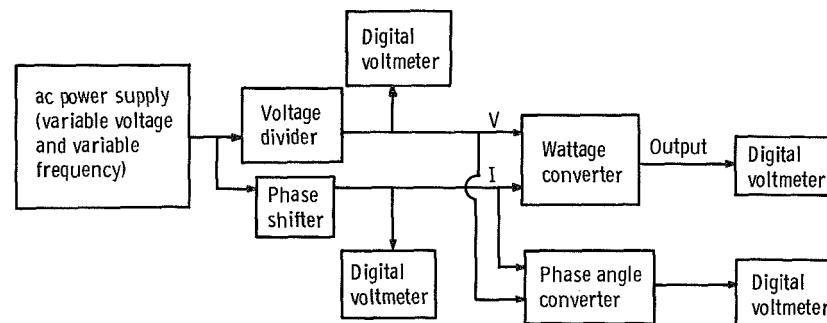


Figure 6. - Test circuit for phase angle test.

input voltages were set at 5 volts rms with average responding DVM's. The input frequency was set at 1 kilohertz. The DVM on the output was the same DVM used in the previous tests. The phase converter converted the phase angle between the V and I signals to a dc voltage.

Drift Test

The purpose of this test was to determine the overall stability of the converter when two input signals were applied. The apparatus for the drift test is shown in figure 7.

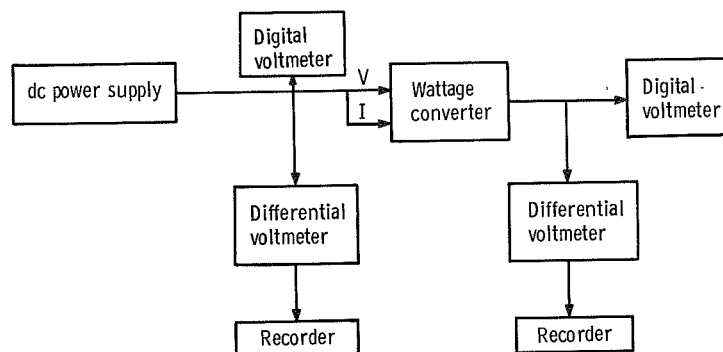


Figure 7. - Test circuit for drift test.

The input voltage to both channels was identical and set for approximately 5.0 volts. The differential voltmeters were of the hand balance type (dials were turned by hand to balance out the input voltages) with a dc output proportional to the difference between the input voltage and the reading of the dials. The recorders were set to indicate ± 5 millivolts for full-scale deflection. Initially, the differential voltmeters were set to balance out the input voltages and any excursion of the input or output voltages would be recorded on the recorders. Limits were placed on the total drift by observing the output voltage excursion and correcting for the input voltage excursion.

Rise-Time Test

The rise-time test was made to determine the time lag between the application of an input signal and the resultant product at the output. The test apparatus is shown in figure 8. The result, expressed as a ratio of the change of the output to the corresponding time delay, is the slewing rate. The rise-time test was conducted by supplying a con-

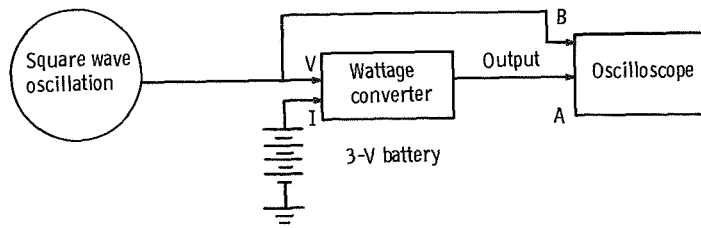


Figure 8. - Test circuit for rise time test.

stant dc voltage to one input channel and a square-wave voltage to the other. For purposes of this test, care was taken to provide an input square wave with a rise rate sufficiently higher than the converter-output rise rate. A measure of the output time lag could be made by observing the output product of the input square wave and the input constant dc voltage.

RESULTS AND DISCUSSION

In general, the results are presented as the percent difference between the calculated output and the observed output. This difference is called the error since the calculated output was at least an order of magnitude more accurate than the observed output.

The multiplier has a full-scale output of ± 10 volts and a maximum input of ± 10 volts. If the input signals are ac voltages, the maximum input voltages are 7.07 volts rms and the maximum average dc voltage output would be 5.0 volts dc. Therefore, full-scale output was defined as ± 5 volts.

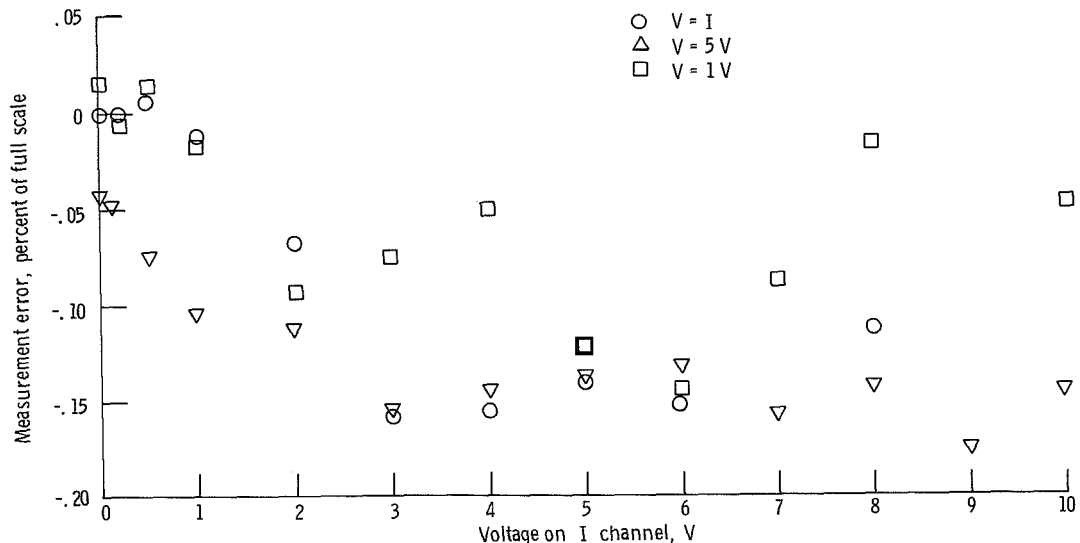


Figure 9. - Measurement error as function of input dc voltage.

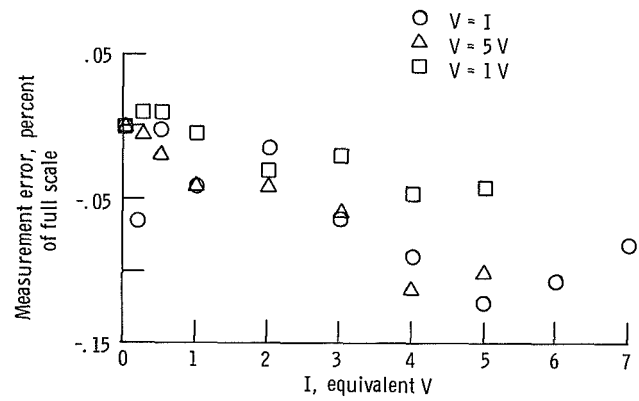


Figure 10. - Measurement error as function of input ac voltage. Frequency, 1 kilohertz; power factor, 1.0.

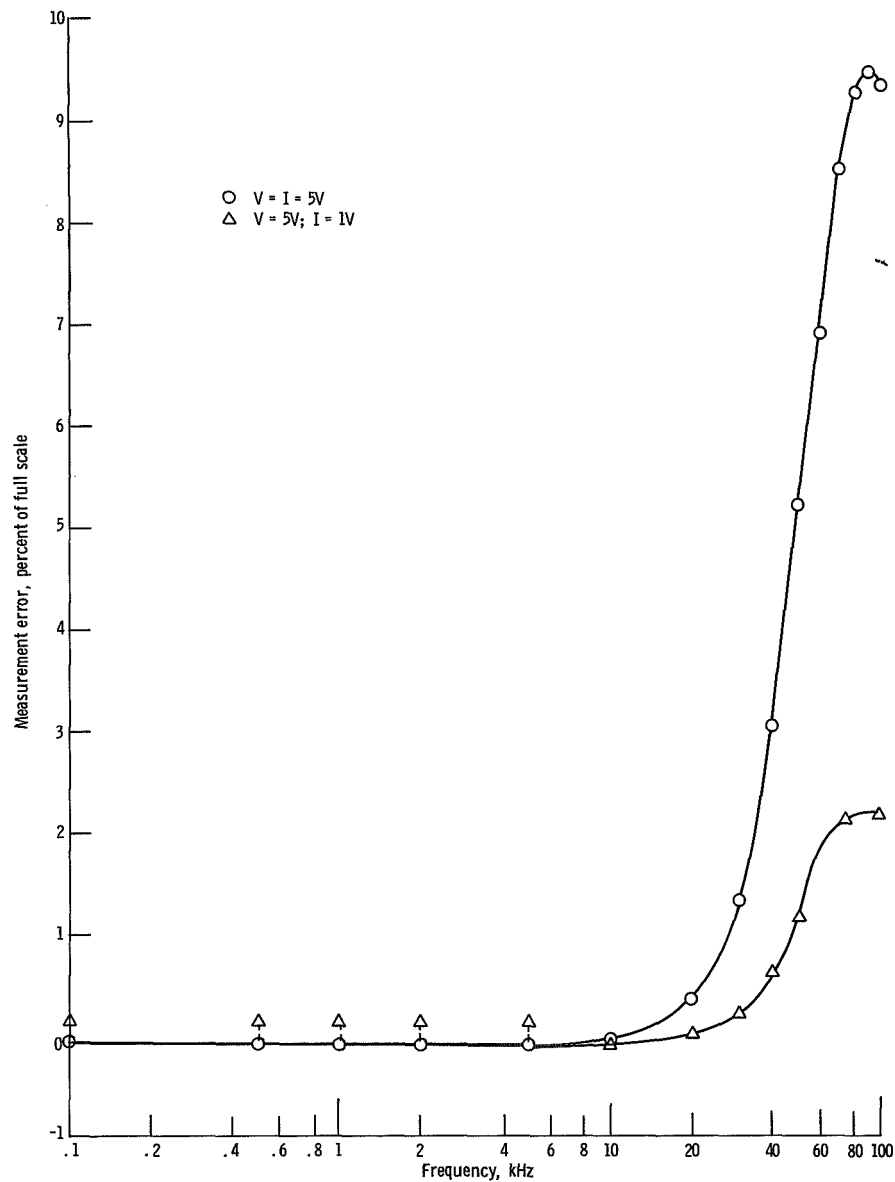


Figure 11. - Measurement error as function of input frequency.

The error is referenced to a full-scale output of 5 volts (i. e. , an error of 5 mV is 0.1 percent error). The measurement error was considered positive if the output reading was greater than the product of the measured input voltages.

Figure 9 summarizes the results of the dc voltage test, and it also illustrates the randomness of the error as a function of input voltages that is characteristic of quarter-square multipliers (ref. 4). The dc voltage error was within +0.02 percent and -0.2 percent of full scale over the input voltage range of 0 to 10 volts. This was after all trim pots were adjusted for minimum offset voltage with both inputs shorted. It is interesting to note that even though the data were collected over a period of 4 months, it was never necessary to re-adjust the trim pots from their initial setting.

The results of the ac voltage tests are shown in figure 10. The measurement error range was from +0.01 percent to -0.12 percent of full scale over the whole range of voltages tested.

The results of the frequency test are shown in figure 11. The error range was from -0.08 percent to +0.4 percent over the frequency range of 100 hertz to 20 kilohertz. At the high frequency end, the error increased rapidly to approximately 2 percent at 35 kilohertz. This occurs when both inputs were 5 volts rms.

The frequency response of analog multipliers and amplifiers are being improved rapidly by the manufacturers, and as better devices become available, higher frequency wattmeters can, of course, be built.

The results of the phase angle tests are shown in figure 12. Because of the uncertainty in the phase angle measurement and the distortion caused by the phase shifter, this test was the least accurate test made on the wattage converter. The phase angle meter is very sensitive to distortion. A considerable amount of distortion was caused

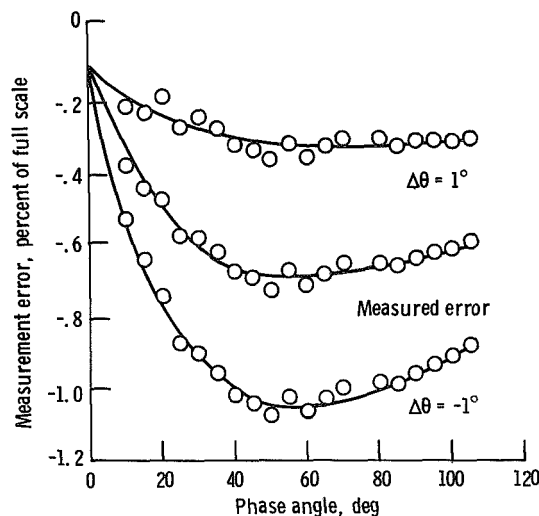


Figure 12. - Measurement error as function of phase angle.

by the phase shifts and produced an error in the phase angle meter. An estimate of this error is $14^{\circ} \pm 1^{\circ}$. The center curve of figure 12 is the converter error assuming all measurements were exact. The upper and lower curves are the converter errors assuming the phase angle measurement was in error by 1° . No correction was made for the possible error due to harmonics in the input voltages. The center curve shows the error increased from -0.1 percent at 0° to about -0.7 percent at 40° . From this point it showed a slight improvement to 90° .

In this particular case, the voltage on the voltage channel was lagging the voltage on the current channel. No apparent difference was observed when the input voltages were reversed such that voltage channel led the current channel. This was to be expected since both input channels were identical.

The results of the drift test conducted over a 1-hour time period are shown in figure 13. One minor division is equal to 0.1 millivolt, and the center line represents 2.500 volts. The chart speed was 0.1 inch per minute. The curve indicates an output of 2.4991 volts and the maximum drift over any 1-hour period (total test time, 20 hr) was less than 0.2 millivolt or 0.004 percent of full scale. The maximum drift over the

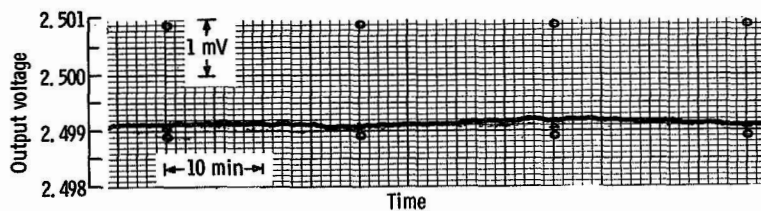


Figure 13. - Output voltage as function of time for constant dc input voltage.

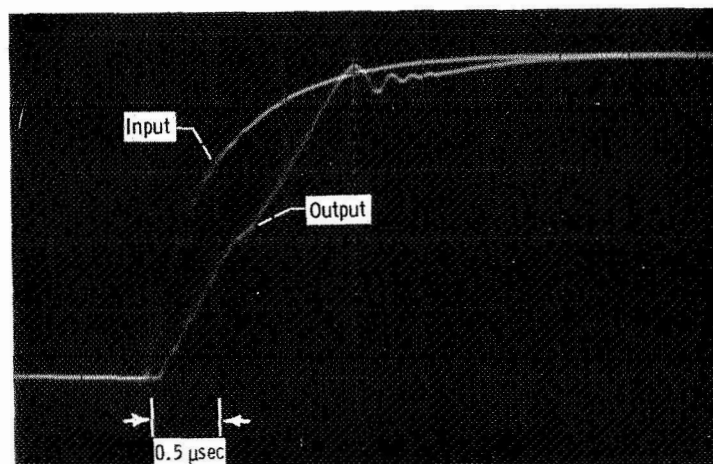
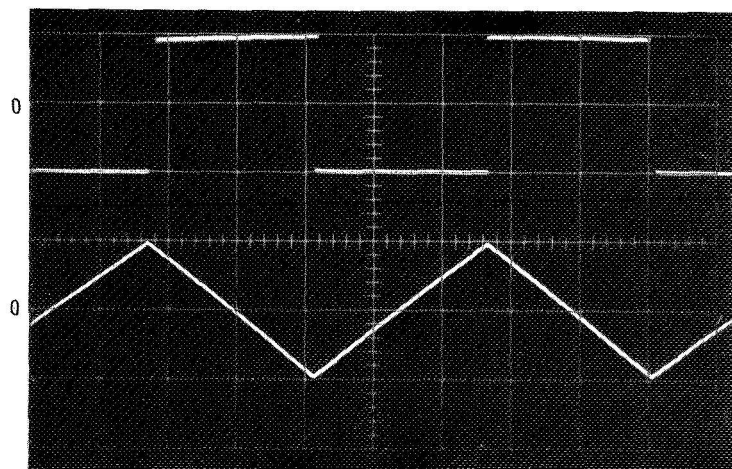


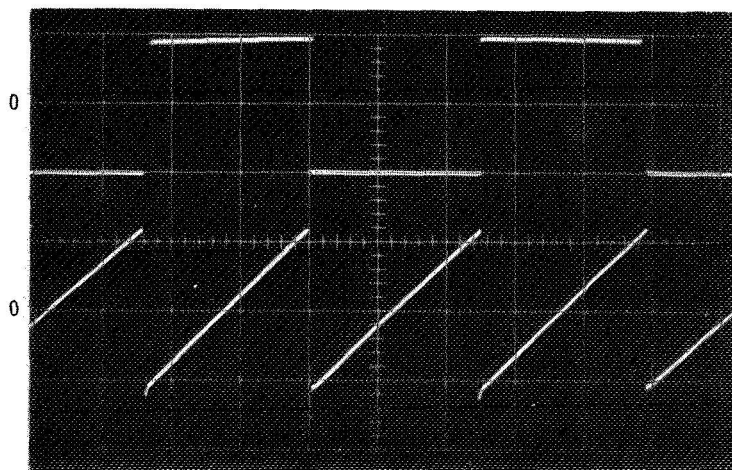
Figure 14. - Input and output waveshapes as function of time.

20-hour test period was found to be ± 0.92 millivolt or 0.02 percent of full scale. Actually, a portion of this drift is attributable to an unavoidable drift of the test input voltage and the drift in the differential voltmeter and recorders, so that the converter drift was somewhat better than this measured 0.02 percent.

The results of the rise-time test are shown in figure 14. The smooth exponential type of trace is that of the square-wave input signal. In this figure the input wave appears rounded, rather than square, because the oscilloscope had a high sweep rate of 0.5 microsecond per division. The amplitude was 9 volts peak to peak. The second multiplier input signal, which consisted of approximately 3 volts dc, is not shown in figure 14. The converter output wave form is a sloped straight line with a slight amount of ringing at the top. Its amplitude was adjusted, in the oscilloscope picture, to coincide with the amplitude of the input square-wave signal. The peak-to-peak output of



(a) Input waveforms.



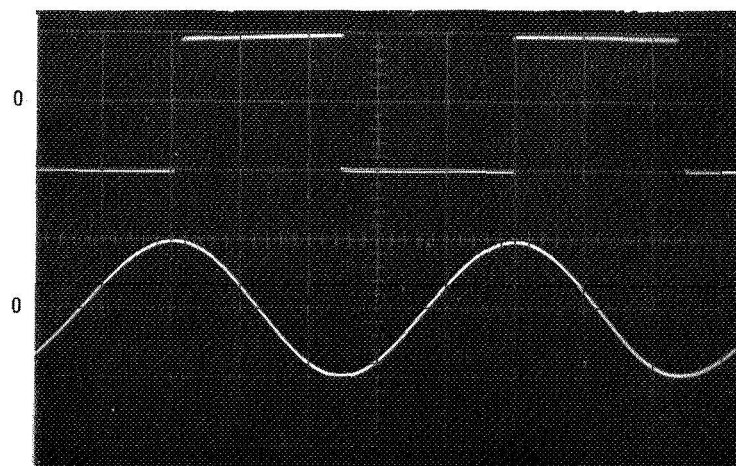
(b) Input waveform (top trace) and product of input waveforms (bottom trace).

Figure 15. - Product of square and triangle waves.

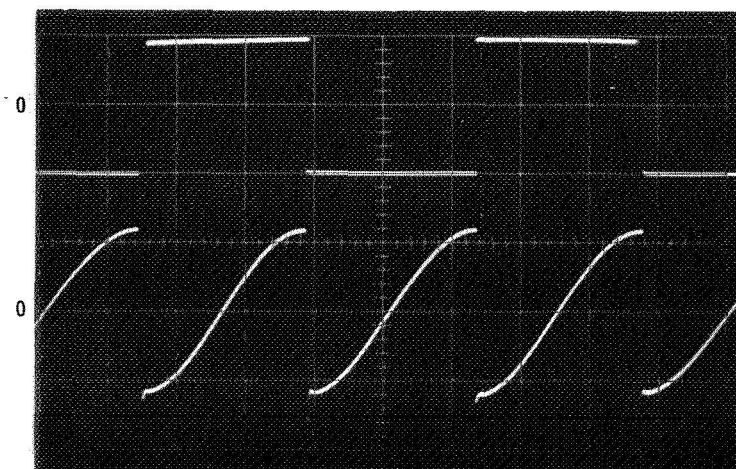
the converter was approximately 3 volts. The time to effect this change is seen to be 3 divisions, or about 1.5 microseconds. This represents a slewing rate of 2 volts per microsecond.

The power the converter draws from the circuit being measured is a function of the attenuator values used and the type of current sensing device. The input resistance of the buffer amplifiers is rated at 10^{11} ohms; therefore, the power into the inputs can usually be ignored. The input shunt capacitance is rated at 5 picofarads, which at 50 kilohertz represents a reactance of 640 kilohms. This reactance puts an upper limit on the values of resistance that can be used in a simple resistive type attenuator, and the power drawn from the measured circuit puts a lower limit on the resistances.

The attenuator used on this wattage converter was a 24:1 attenuator with a total input resistance of 120 kilohms. At a 120-volt rms input, the power drawn by the atten-



(a) Input waveforms.

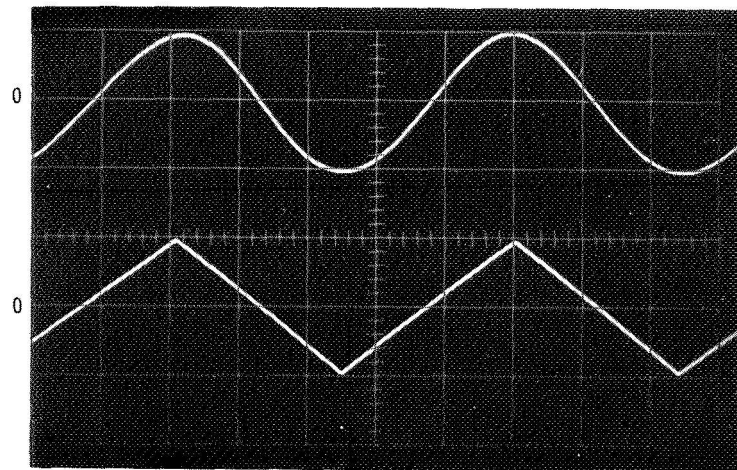


(b) Input waveform (top trace) and product of input waveforms (bottom trace).

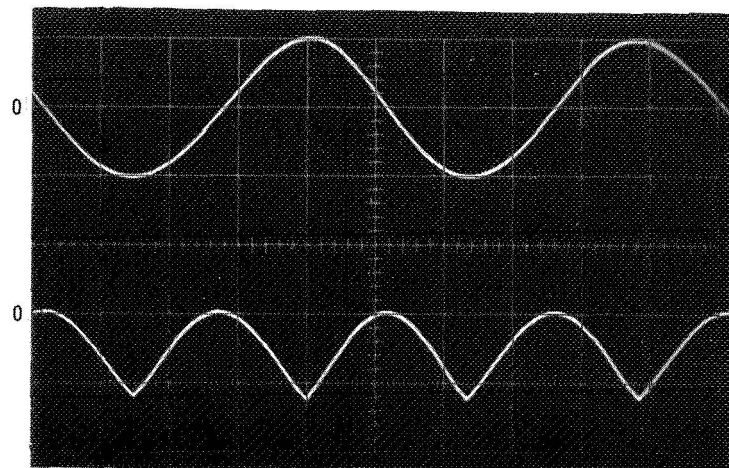
Figure 16. - Product of square and sine waves.

uator is 0.12 watt. The current probe used with this converter had an insertion resistance of 0.0002 ohm and a rating of 50 amperes rms with a 5-volt rms output. The loss in the probe at 50 amperes is 0.5 watt and the loss in the converter current input is less than 1 microwatt. At 120 volts rms and 50 amperes rms, the total full-scale power being measured is 6000 watts and the loss is 0.62 watt or 0.01 percent of full scale.

To illustrate the operation of the wattage converter several waveforms were multiplied together and the output recorded on an oscilloscope. The waveforms were a sine wave, a square wave, and a sawtooth wave. No data were taken with these waves, but it is interesting to compare the experimental results with the expected results. The products of various waveforms are shown in figures 15 to 17. The input voltages were approximately 10 volts peak to peak and the input frequency was 1 kilohertz. Figure



(a) Input waveforms.



(b) Sine waveform (top trace) and product of sine waveforms (bottom trace).

Figure 17. - Product of sine and triangle waves.

15(a) illustrates the two input signals with their phase relation and figure 15(b) shows the product of the two input voltages. The square wave input is also shown in figure 15(b) to illustrate the phase relation. The wattage converter inverts the output such that the output is actually the negative product of the inputs. Figure 16 is the same as figure 15 except that the triangle waveform is replaced with a sine wave. The average output of the converter in figures 15 and 16 over one period is zero.

Figure 17 illustrates the product of a triangle wave and a sine wave. The average output (again inverted) is not zero since the product is never less than zero.

CONCLUSIONS

A solid-state wattage-to-voltage converter was designed, built, and tested. The conclusions drawn from the testing are as follows.

1. The principle of using an analog multiplier as the basis of a wattmeter has been proven to be a sound concept.
2. The device described is capable of measuring power over a frequency range of dc to 15 kilohertz with an accuracy of 0.2 percent of full scale. (This does not include errors due to the voltage attenuator or the current transformer.) The error increases to ± 2.0 percent at 35 kilohertz.
3. The output has a 0- to 10-volt range with a slewing rate of approximately 2 volts per microsecond. This gave the converter the capability of measuring power in waveforms such as square waves, pulses, spikes, rectified sine waves, etc. When an oscilloscope or recorder is used on the output, the converter can also be used to measure instantaneous power in nonrepeating waveforms.
4. The stability measured over a 20-hour period showed the drift to be less than 0.02 percent of full scale.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio,
120-27.

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